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FIRST OBSERVATIONS ON THE INTERNAL ERODIBILITY OF SOME SOIL-LIKE WEATHERED ROCKS BY MEANS OF HOLE EROSION TESTS

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EXTENDED ABSTRACT

Il fenomeno dell'erosione interna dei terreni è tra le principali cause di rottura di opere idrauliche (e.g., dighe e argini), sponde fluviali e pendii naturali (e.g., innesco di dissesti superficiali). Tale fenomeno spesso pregiudica la sicurezza di dighe e di opere idrauliche per la mitigazione del rischio alluvionale, talvolta con rilevanti conseguenze in termini sociali ed economici.

L'erosione interna è un fenomeno complesso che, a livello generale, consiste in un graduale distacco e trasporto di granuli dal volume di terreno ad opera delle forze generate dai moti di filtrazione dell'acqua. Questo studio focalizza l'attenzione sul meccanismo di erosione da perdite concentrate. Nelle infrastrutture idrauliche quali le dighe in materiali sciolti, tale fenomeno è solitamente associato allo sviluppo di processi di erosione all'interno di fessure preesistenti che possono essere generate da cedimenti differenziali, scadenti operazioni di compattazione durante le fasi costruttive, anomalie presenti in fondazione o lungo l'interfaccia di strutture inglobate all'interno del rilevato, come ad esempio condotte e gallerie. In questi casi, gli sforzi di taglio prodotti dai moti di filtrazione causano il distacco e il conseguente trasporto di particelle di terreno dalla superficie interna delle fessure, causandone il progressivo allargamento. Per caratterizzare e modellare questo particolare meccanismo di erosione interna dei terreni, WAN & FELL (2004a, 2004b) hanno sviluppato i test di laboratorio "*Slot Erosion Test*" (SET) e "*Hole Erosion Test*" (HET). Tali prove consentono di caratterizzare l'erodibilità dei terreni grazie alla determinazione dello sforzo di taglio critico di innesco dell'erosione e della velocità con cui tale fenomeno si sviluppa.

Se le opere idrauliche sono realizzate in ambienti climatici caldo-umidi, l'ammasso roccioso che costituisce il substrato può risultare fortemente alterato. I processi di alterazione indotti da agenti atmosferici possono modificare la matrice rocciosa nelle sue caratteristiche mineralogiche, di resistenza, di colore e l'ammasso roccioso in termini di grado di fratturazione. Se il processo di alterazione è particolarmente spinto, l'ammasso risulta un materiale con caratteristiche assimilabili a quelle di un terreno. L'azione degli agenti atmosferici può avere marcate influenze sulle proprietà fisiche (e.g., porosità e densità), meccaniche (e.g., resistenza e rigidezza) e idrauliche (e.g., permeabilità) del *parent material*. In letteratura, solo poche ricerche hanno riguardato l'erodibilità di materiali rocciosi fortemente alterati. In questo studio, una serie di indagini di laboratorio mediante *Hole Erosion Test* è stata condotta su alcuni campioni di rocce fortemente alterate (*soil-like*) provenienti dall'Africa. Tale test consente di simulare in laboratorio il fenomeno dell'erosione da perdite concentrate grazie all'analisi degli effetti del passaggio di acqua attraverso un foro praticato nel campione stesso. L'obiettivo dello studio è quello di investigare la suscettibilità di tali materiali allo sviluppo di fenomeni di erosione interna. A tale scopo, una apposita apparecchiatura di prova è stata riprodotta in laboratorio seguendo i suggerimenti di WAN & FELL (2004a, 2004b).

I primi risultati ottenuti evidenziano che alcuni campioni risultano potenzialmente predisposti all'innesco di fenomeni di erosione interna con velocità variabili da estremamente a moderatamente rapide. I risultati di questa ricerca forniscono utili indicazioni riguardanti il ruolo dei processi di alterazione da agenti atmosferici sulla modifica delle proprietà idrauliche dei materiali rocciosi e, infine, attestano l'utilità del test HET per l'analisi dell'erosione da perdite concentrate in rocce fortemente alterate. Ulteriori ricerche saranno necessarie per approfondire il ruolo svolto da alcuni fattori (e.g., composizione mineralogica e caratteristiche tessiturali) che regolano l'erodibilità e per meglio caratterizzare la variabilità dei parametri geotecnico-idraulici derivati dalla prova HET.

ABSTRACT

Concentrated leak erosion involves the initiation and evolution of soil erosion along a pre-existing crack or micro-fissure due to seeping water and it can be often source of severe safety issues in man-made hydraulic infrastructures. In laboratory, this peculiar internal soil erosion mechanism can be simulated using the Hole Erosion Test (HET). The erodibility of highly weathered rock materials is poorly investigated in literature, although these materials often interact with embankment dams or levees. In this study, a series of HET tests were performed on some soil-like weathered rock specimens, coming from a project-site located in Africa, to investigate their susceptibility to develop internal erosion in concentrated leaks. Although affected by a certain degree of variability, the first outcomings have highlighted that some samples are potentially susceptible to be affected by internal erosion with rates from moderately to extremely rapid. The results of this research provide useful insights in the implication of weathering processes in modifying hydraulic properties of rock materials. Eventually, this study testifies that the Hole Erosion Test can be suited to study the progressive erosion of highly decomposed rocks.

Keywords: *erodibility, concentrated leak erosion, hole erosion test, internal erosion; weathered rocks*

INTRODUCTION

Internal soil erosion is an important factor in controlling the occurrence of failures in man-made hydraulic works (e.g., embankment dams, dikes, levees) (Fell & Fry, 2007), in fluvial terraces or stream banks (Crosta & Prisco, 1999; Daly *et alii*, 2015) and in natural slopes (e.g., shallow landslides, debris flows, gullies) (Uchida *et alii*, 2001; Hencher, 2010; Wilson *et alii*, 2013; Schilirò *et alii*, 2018). The rupture of earth dams or of flood mitigation measures (e.g., dikes, levees) can result in relevant social and economic consequences (Foster *et alii*, 2000; Richards & Reddy, 2007; Briaud, 2008). For example, Foster *et alii* (2000) reported that more than 45% of large embankment dams ruptures and accidents are related to the occurrence of internal erosion processes.

Internal erosion is a complex phenomenon consisting of a gradual detachment and transport of particles from the soil matrix due to forces generated by water seeping (Fell & Fry, 2007). According to Bonelli (2013), four main mechanisms of initiation and progression of soil internal erosion can be identified (Fig. 1): i) concentrated leak erosion, ii) regressive erosion, iii) contact erosion and iv) suffusion. Concentrated leak erosion occurs in case of seeping water along pre-existing defects (e.g., cracks, micro-fissures, burrows, roots) into the soil volume (Fig. 1a). Regressive erosion, also known as backward erosion, involves the formation and evolution of a pipe within an embankment by progressive erosion of soil particles when critically high hydraulic gradients are attained (Fig. 1b). Contact erosion can initiate along the boundary between two soil layers characterized by different grain size and hydraulic conductivity (Fig. 1c), whereas suffusion concerns the gradual detachment of fine particles from the soil matrix producing a loose instable framework of coarse soils (Fig. 1d).

In literature, several methods were proposed for simulating the different internal erosion mechanisms and therefore investigating erodibility of soil materials (Wan & Fell, 2004a, b; Fell & Fry, 2007). This study deals with concentrated leak erosion. In hydraulic infrastructures this phenomenon is usually associated to the development of erosion processes inside cavities (e.g., cracks) that can be produced by differential settlements, poor compaction operations during construction or by soil-structure boundaries (e.g., along conduits). In these cases, seepage forces concur to detach soil particles from the internal surface of the crack, carrying them away and progressively leading to its enlargement. To characterize and model this process, Wan & Fell (2004a, 2004b) developed the Slot Erosion Test (SET) and the Hole Erosion Test (HET). These tests allow to characterize the erodibility of soils in terms of both hydraulic shear stress thresholds and erosion rates.

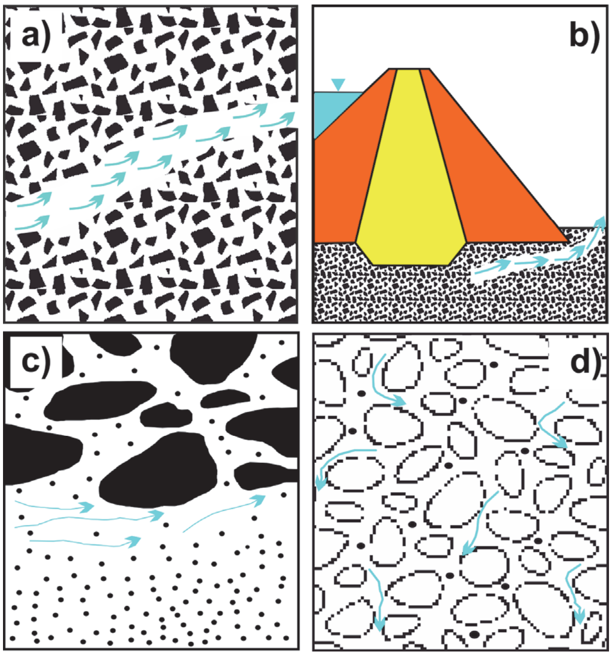

Fig. 1 - Four main types of internal erosion: a) concentrated leak erosion, b) backward erosion piping, c) contact erosion and d) suffusion

In tropical-subtropical environment, earth dams are often founded on rock masses highly weathered for exposition to peculiar climatic conditions during their geological history (SELBY, 1993; ANON, 1995). Weathering processes modify fresh rocks causing changes in mineralogy, color and degree of fracturing up to reducing the rock mass to a soil-like material. Weathering generally affects physical (e.g., porosity, density), mechanical (e.g., strength, stiffness) and hydraulic (e.g., permeability, saturated conductivity) properties of the parent rock material (IRFAN & DEARMAN, 1978; HENCHER, 2006).

In literature, very few researches (HENCHER, 2010) deal with erodibility of highly weathered rock materials. In this study, a series of HET tests were performed on some soil-like weathered rock specimens, coming from a project-site located in Africa, to investigate their susceptibility to develop internal erosion in concentrated leaks. To this purpose, a HET facility was constructed in laboratory following the suggestions of WAN & FELL (2004a, 2004b).

HOLE EROSION TEST (HET): THEORETICAL FRAMEWORK AND TESTING EQUIPMENT

The Hole Erosion Test simulates concentrated leak erosion in soil specimens by imposing a water flow along a pre-drilled hole. This experimental procedure allows to measure the soil erodibility properties that can be expressed by the rate of erosion when a given hydraulic shear stress is attained and by the ease of initiating progressive erosion of soil particles (WAN & FELL, 2004b).

Generally, a 6-mm diameter hole is drilled along the longitudinal axis of undisturbed tube soil samples or soil specimens compacted into a standard Proctor mold. Subsequently, specimens are accommodated into the testing equipment (Fig. 2a) and subjected to water flow through the hole under a constant hydraulic gradient. Progressive and accelerating erosion is induced by increasing incrementally the hydraulic head difference between upstream and downstream of the tested specimen. During the test, the actual hydraulic gradient across the specimen can be detected from the heights of the water columns inside plastic standpipes (Fig. 2a) while the flow rate through the specimen is obtained from the measure of the volume of flowing water at selected time intervals. Once progressive erosion is triggered, the upstream hydraulic head is kept constant until the end of the test. According to the suggestions of WAN & FELL (2004b), the test should be stopped before the pre-drilled hole is enlarged to the side of the mold, or before the flow rate becomes too high to be measured accurately by the setup. After the test, the specimen is extruded from the mold to describe the shape of the final hole and to measure its diameter. By means of a caliper, the final hole diameter can be measured from carefully sliced specimens or from casts in plaster. This measurement can be sometimes affected by uncertainties due to irregularities of the hole at the end sides of the sample, especially when weaker materials are tested. As a result of eddies produced at the entrance and exit of the water flow, anomalous detachments of soil portions from the end faces of the specimen can occur,

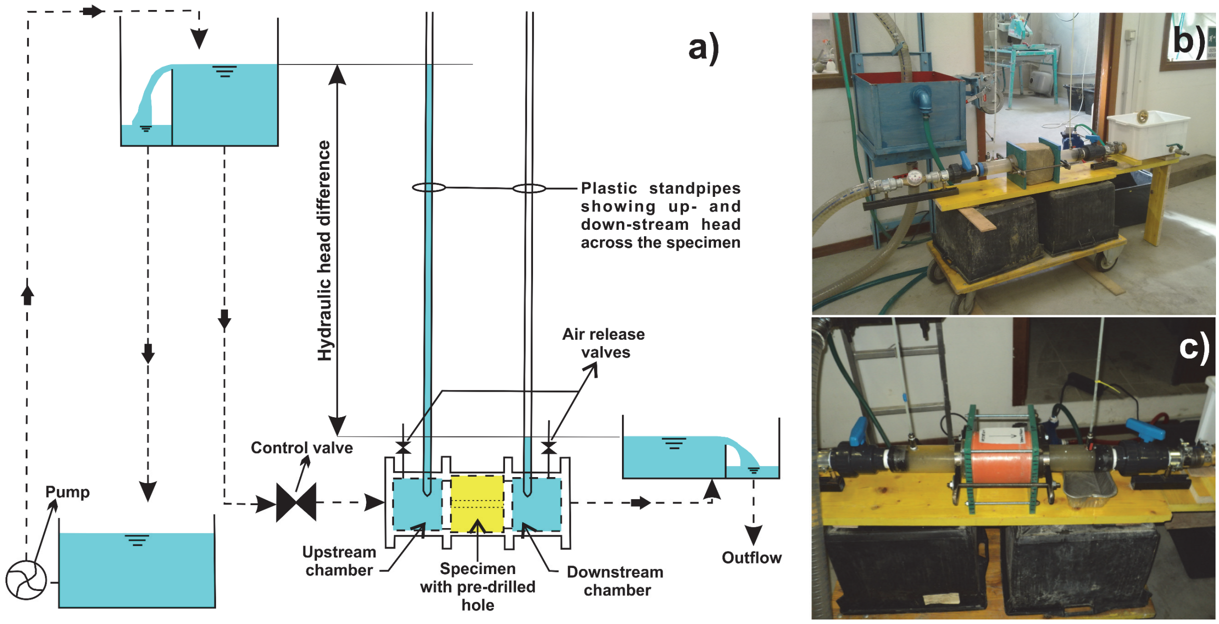

Fig. 2 – a) Sketch of the Hole Erosion Test device (redrawn and modified from WAN & FELL, 2004b); b) HET device used in this study and example of compact cubic sample; c) example of sample arrangement in case of weak material

making problematic the reliable determination of the final hole diameter. As proposed by WAHL *et alii* (2008), this problem can be reduced by installing contact end plates with an orifice opening of 15 or 25 mm.

The HET erodibility parameters are expressed by the following equation (WAN & FELL, 2004a, 2004b):

$$\dot{\varepsilon}_{HET} = C_e(\tau_{HET} - \tau_c) \qquad (1)$$

where $\dot{\varepsilon}_{HET}$ is the erosion rate per unit surface area of the hole (kg/s/m^2), C_e is a constant (s/m), often reported as Coefficient of Soil Erosion, τ_{HET} is the applied shear stress along the axial hole at time *t* (Pa) and τ_c is the critical shear stress for initiation of erosion (Pa). WAN & FELL (2004b) observed that C_e assumes small values ranging several orders of magnitude (usually from 10^{-1} to 10^{-6}). Therefore, the same authors suggested to use the Erosion Rate Index (I_{HET}), which is defined as:

$$I_{HET} = -log_{10}\, C_e \qquad (2)$$

I_{HET} allows to classify soil erodibility into six classes: from extremely rapid (I_{HET} < 2) to extremely slow (I_{HET} > 6). I_{HET} values greater than 6 represent soils that do not show measurable signs of erosion during the tests.

HET data elaboration is not a straightforward procedure. Currently, standard agencies such as American Society for Testing Materials (ASTM) give no information regarding both testing procedure and data analysis. In brief, referring to WAN & FELL (2004a, 2004b), data measured during the test (i.e., hydraulic gradient across the specimen and flow rate), along with the initial and final size of the hole, allow to indirectly compute $\dot{\varepsilon}_{HET}$ and τ_{HET}. Subsequently, τ_c and C_e are determined by using a specific graphical procedure on the plot $\dot{\varepsilon}$ versus τ_{HET}. The typical resulting τ_{HET}-$\dot{\varepsilon}_{HET}$ plot is a V-shaped graph where τ_c is defined as the X-intercept of the best-fit line of the V-right half while C_e represents its slope. Further details about HET data analysis procedures, together with alternative elaboration methods, are reported in literature (WAN & FELL, 2004b; BONELLI *et alii*, 2006; BONELLI & BRIVOIS, 2007).

In this study, a HET test apparatus was reproduced at the S.G.L. (Servizi Geotecnici Liguri) Geotechnical Laboratory of Vado Ligure (Savona, Italy) following technical suggestions of WAN & FELL (2004a, 2004b). Unlike the HET equipment used by such authors, which was designed for maximum test heads of 1200 mm, the constructed testing device allows to reach maximum applicable hydraulic head of 3000 mm.

TESTED MATERIALS AND EXPERIMENTAL PROCEDURE

Tested samples come from a project-site in Africa and consist of soil-like highly weathered rocks deriving from deep weathering processes affecting meta-granites and phyllites. Undisturbed individual samples, approximately cubic in shape, were manually taken from the side-wall of trenches by using field cutting and sampling device. In case of cemented and stiffer materials, a portable rock-chop saw was also used to perform sampling. During sampling operations, sample orientation was recorded. Samples were then sealed and transferred to the laboratory and stored in a humidity room. For HET testing, the more compact samples were then carefully trimmed with a steel blade into cubes so as end faces precisely adhered watertight to the end adapter plates (Fig. 2b). There was considerable difficulty in preparation of samples made up of weaker materials. In these cases, samples were accurately trimmed into cylinders and then accommodated into a PVC pipe sleeve and the space between the sample and the PVC pipe was filled with moldable material (e.g., plasticine) (Fig. 2c). Subsequently, an 8-mm diameter hole was performed using a drill press to minimize as much as possible disturbance to the sample. Eventually, the hole was cleaned from drilling residuals using a brush.

In this study, 10 HET tests had been performed. Throughout the test, the flow rate was measured every 30 seconds by the operator using a water meter while the hydraulic head was recorded every 1 minute on the plastic standpipes. The initial hydraulic head was set to 50 mm and then increased incrementally. During the performed test program, the highest applied hydraulic head was set to 1800 mm. When progressive erosion was observed, the test was continued at a constant hydraulic gradient for about 45 minutes. Basic physical and index properties of the samples were determined from the disaggregated soil material obtained during the HET sample preparation. Following ASTM standard methods, the laboratory test program included grain size analyses, specific gravity of solids and Atterberg limits determinations. Moreover, intact sample pieces were used to determine natural unit weight by means of the buoyancy technique.

RESULTS AND DISCUSSION

Index properties pertaining to the 10 HET samples are listed in Tab. 1. Overall, according to the USCS soil classification system, tested materials prevalently consist of silts and very fine sands with low plasticity (ML) and secondly of silty sands (SM) and silty clays with low plasticity (CL). Meta-granite rock weathered products (MGT) are usually characterized by low clay contents, usually ranging approximately between 8 and 18%, and abundant percentages of sand (maximum about 60% in SM) and silt (maximum about 48% in ML) with a gravel content, when present, lower than 1%. The specific gravity of solids and the natural unit weight are somewhat constant and comprised in the range 2.72-2.82 and 17.0-17.6 kN/m^3, respectively. Phyllite rock alteration products (PHY) also exhibit high contents of silt (about in the range 40-51% in ML) and sand (maximum about 50% in SM). In PHY group, gravel reaches slightly higher content (maximum about 5%) than in MGT materials. However, these ones show higher clay content (maximum percentage of about 25% in CL). Moreover, both specific gravity of solids and unit weight show greater variability. The former is in the range 2.57-2.78 while the latter varies between 17.5 and 21.4 kN/m^3.

In terms of plasticity, PHY materials show, on average, a higher Plasticity Index than MGT materials, probably due to the higher content in clay. However, some samples belonging to both groups, and characterized by very low clay contents (lower than 8%), showed no plasticity features (Tab. 1).

Sample n°	Material type	G_S	γ [kN/m^3]	USCS	PI [%]	I_{HET}
1	PHY	2.78	17.5	SM	4.2	N.P.
2	PHY	2.61	18.3	ML	N.P.	N.P.
3	PHY	2.57	17.0	ML	9.2	2.6
4	PHY	2.69	18.5	ML	14.1	3.2
5	PHY	2.67	21.2	CL	18.1	4.1
6	PHY	2.70	21.4	ML	11.7	1.7
7	MGT	2.82	N.P.	ML	N.P.	3.6
8	MGT	2.72	17.0	ML	7.0	3.4
9	MGT	2.77	17.4	SM	N.P.	5.0
10	MGT	2.78	17.6	ML	7.1	3.1

Tab. 1 – Index properties of tested materials and Erosion Rate Index I_{HET} (PHY: phyllite rock weathered products; MGT: meta-granitic rock weathered products; G_S: specific gravity of solids; γ: natural unit weight; PI: Plasticity Index)

HET test results (Tab. 1) highlight that most of the samples are susceptible to develop progressive erosion. For the tested samples, the obtained I_{HET} ranges from a minimum value of 1.7 to a maximum one of 5.0. Generally, PHY showed more varied erodibility. According to the classification of the erosion rate proposed by WAN & FELL (2004a; 2004b) (Fig. 3), based on the value of I_{HET} sample n° 6 can be affected by extremely rapid erosion ($I_{HET} < 2$), sample n° 3 by very rapid erosion ($2 < I_{HET} < 3$), sample n° 4 by moderately rapid erosion ($3 < I_{HET} < 4$) and sample n° 5 by moderately slow erosion ($4 < I_{HET} < 5$). For MGT samples I_{HET} results less variable and ranging between 3.1 and 5.0. Three samples (n° 7, 8 and 10) can be affected by moderately rapid erosion ($3 < I_{HET} < 4$) while one sample (n° 9) by very slow erodibility ($5 < I_{HET} < 6$).

Two PHY samples did not exhibit progressive erosion during the test, even at the maximum applied hydraulic head of 1800 mm. As reported by some researchers (BONELLI & BRIVOIS, 2007; WAHL *et alii,* 2008), these materials are usually characterized by highly cemented and sometimes lithified texture and are likely to be rock-like materials rather than soils and they could be virtually included into the group 6 (extremely slow erosion).

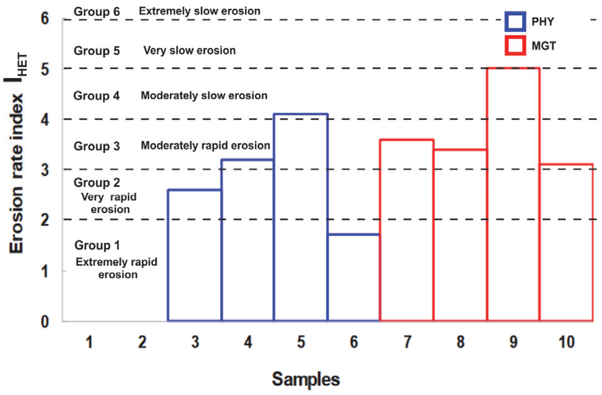

Fig. 3 – Classification of the erodibility for the tested materials according to the Erosion Rate Index values

The first results of this research show that, like many geotechnical properties of soils and rocks (PHOON & KULHAWY, 1999; PEPE *et alii*, 2017), also the Erosion Rate Index is affected by a certain degree of variability. Such variability could be related to the mineralogical features of the tested materials. It is known from literature (WAN & FELL, 2004b) that erodibility can be influenced by clay mineralogy (e.g., presence of smectite clays) or by cementing materials (e.g., iron oxide) that can produce hard crusts around soil particles. Ongoing researches focusing on mineralogical and petrographic aspects should improve the characterization of factors regulating erodibility behavior of the studied materials.

CONCLUDING REMARKS

Internal soil erodibility related to concentrated leak erosion mechanism represents a critical issue for the safety of man-made hydraulic infrastructures. In this study, we investigated the susceptibility to develop internal erosion in concentrated leaks of some soil-like weathered rocks through the Hole Erosion Test (HET), an experimental procedure which allows to reproduce in laboratory erosion processes developing along pre-existing defects such as cracks and micro-fissures. We tested 10 samples coming from a project-site located in Africa. The first outcomings highlighted that 6 samples are potentially prone to progressive erosion initiation (with erosion rates from extremely to moderately rapid). However, further researches addressed to investigate the factors influencing erodibility should improve the comprehension of the variability that affects HET parameters. Nevertheless, the results of this research revealed that also highly weathered rocks could be source of internal erosion issues. Eventually, this study testifies that the HET can be suited to study progressive erosion of highly decomposed rocks.

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